Image Segmentation with Parametric Part Models

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PROJECT SUMMARY

This proposal is concerned with the consequences of a newly introduced shape representation model in computer vision — *Superquadrics* that opened up new ways of shape reconstruction from images. Although their descriptive power is not as large as that of generalized cylinders, they encompass basic geometric shapes such as parallelepipeds, cylinders, elipsoids and shapes inbetween which can be further subjected to global shape deformations. Due to the underconstrained nature of the whole visual reconstruction problem superquadrics introduce new constraints or information by imposing a family of possible shapes that parts can have. This overconstraint comes from using models defined by a few parameters to describe a large number of image points. This overdetermined optimization problem can be solved by standard mathematical techniques.

The principal investigators of this proposal introduced a fast and reliable method for recovery of single deformable superquadric models from range images. Even with its current shortcomings (single part assumption) the method has been concidered for mail-piece handling automatization and for haptic object recognition with multi-fingered dextrous robotic hands. To become a generally accepted method for visual shape reconstruction, superquadric recovery must address two problems: first, their role, or the role of part level models in general, in partitioning or segmentation of scenes and objects into such parts, and second, demonstrating that input data for this kind of visual reconstruction can come from different sources or visual cues (stereo, occluding contours, shading and color) and not only from range data as is the case now.

In this proposal we suggest to solve the two above mentioned problems. We will use some of the new ideas from vision research, robotics and computer graphics regarding sensory fusion and description of geometrical constraints, the basis of our research, however, will be our past experience and results in this area.

Segmentacija slik s parametričnimi modeli na ravni delov

Povzetek projekta

Projekt se ukvarja s posledicami novih modelov za predstavo oblik v računalniškem vidu, ki se imenujejo *superelipsoidi* in ki so odprli nove možnosti rekonstrukcije oblike iz slik. Čeprav je njihova zmožnost opisovanja manjša od posplošenih cilindrov, pa superelipsoidi vseeno lahko modelirajo osnovna geometrijska telesa, kot so paralelepipedi, valji, elipsoidi in oblike med temi telesi, ki jih je moč še dodatno deformirati z globalnimi deformacijami oblike. Ker v sami vizuelni rekonstrukciji ni dovolj omejitev, da bi lahko enolično določili tridimenzionalne oblike iz dvodimenzionalnih slik, superelipsoidi uvedejo nove mejne pogoje s tem, da določijo družino vseh možnih oblik, ki jih deli lahko imajo.

Glavna raziskovalca predloženega projekta (doc. dr. Franc Solina s Fakultete za elektrotehniko in računalništvo v Ljubljani in prof. dr. Ruzena Bajcsy z University of Pennsylvania v Philadelphiji) sta skupaj razvila hitro in zanesljivo metodo rekonstrukcije posameznih deformiranih superelipsoidnih modelov iz globinskih slik (tridimenzionalnih točk). Čeprav je metoda še pomanjkljiva v tem, da obravnava le predmete sestavljene iz enega samega dela, pa se njena uporabnost že preizkuša za avtomatično sortiranje poštnih pošiljk in manipulacijo oziroma prepoznavanje predmetov z gibljivimi večprstnimi robotskimi rokami. Da bi postala splošno priznana metoda za vizualno rekonstrukcijo oblike, mora rekonstrukcija z superelipsoidi rešiti naslednja dva problema: prvi problem je vloga superelipsoidov oziroma geometrijskih modelov na ravni posameznih delov pri segmentaciji, to je razčlenitvi scene oziroma členjenih predmetov na posamezne komponente oziroma dele, ki jih lahko modelirajo posamezni superelipsoidi, drugi problem pa je kako poleg ali namesto globinskih slik uporabiti tudi druge vrste vizualnih informacij (stereo, konture, senčenje in barve) za njihovo rekonstrukcijo.

V okviru tega projekta predlagamo rešitev teh dveh problemov. Uporabili bomo nekatere nove ideje s področja umetnega vida in robotike, ki se nanašajo na integracijo senzorjev in opisa geometrijskih mejnih pogojev, delo pa bo temeljilo predvsem na naših dosedanjih izkušnjah in rezultatih.

Image Segmentation with Parametric Part Models

PROJECT PROPOSAL

1 Introduction

This proposal is concerned with the consequences of a newly introduced shape representation model in computer vision that opened up new ways of shape reconstruction. This new model is a parametric family of shapes called superquadrics. Their descriptive power is not as large as that of generalized cylinders, yet large enough to encompass basic geometric shapes such as parallelepipeds, cylinders, elipsoids and shapes inbetween which can be further subjected to global shape deformations. Superquadrics were introduced because the predominant shape reconstruction methods in computer vision which are based on a stepwise reduction of data in general fail when confronted with natural scenes where image formation parameters can change abruptly from image point to image point [36]. Because of those abrupt changes and noise in images low level model such as edges, corners and surface patches are error-prone. To perform any reasoning (navigation, manipulation, recognition) only the most relevant low level models must be selected or models of larger scale must be constructed out of those low level models. This step, however, is very difficult. Due to the underconstrained nature of the whole visual reconstruction problem new constraints or information must be introduced at this point. By imposing a family of possible shapes that parts can have, superquadrics can form overconstrained estimates of their parameters. This overconstraint comes from using models defined by a few parameters to describe a large number of image points. This overdetermined optimization problem can be solved by standard mathematical techniques.

The principal investigators of this proposal introduced a fast and reliable method for recovery of single deformable superquadric models from range images [4,43,46]. Even with its current shortcomings (single part assumption) the method was concidered for mail-piece handling automatization [42,44,45] and for haptic object recognition with multifingered dextrous robotic hands [1]. Before superquadric recovery can be generally accepted as a viable method for visual reconstruction, two open problems remain. The first and the most important problem is segmentation. Superquadrics have been shown to model parts that correspond to the human notion of parts very naturally [36]. Hence, one would expect that superquadrics could play a large role in partitioning or segmenting scenes and objects into such parts. The second problem is the form of the input data for this kind of visual reconstruction. So far, 3-D points were used, obtained by passive range imaging. It has to be demonstrated that besides 3-D position other cues such as surface normals and occluding contours could also be used. In fact, compact volumetric models such as superquadrics could be a vehicle for integrating information from several different visual cues. Other investigators partially addressed or are addressing these two problems [37,14]. We attacked both problems in the past [42,43]. A comprehensive and reliable solution, however, is still missing. The goal of the proposed work is to solve these problems.

The rest of the project description is divided into two parts. Section 2 is the scientific part of the project proposal. It gives a more detailed background on the shape reconstruction problem, describes the proposed work and points out the possible impact. Section 3 introduces the project personnel, describes the available facilites, the benefits for both parties of the proposed international cooperation and organization of work. References are given at the end.

2 Scientific goals

2.1 Background

One of the major goals of computer vision is to recover such descriptions of the physical world that enable locating, handling and identifying objects. Since shape information plays a crucial part in these activities, a substantial effort was devoted to identify proper models for shape representation. Different shape reconstruction methods introduced different shape models, that is models that fitted into the particular reconstruction philosophy (bottom-up, top-down or a combination of the two). At the same time, models can have an influence on the selection of particular recovery methods so that new models for shape representation can lead to new methods for shape recovery and segmentation.

Segmentation of images into regions corresponding to single objects or their parts is one of the harder problems in computer vision. Recognition of objects would be easier for a vision system if the system knew which areas in an image correspond to single objects. Segmentation, on the other hand, would also be simpler if the identity of objects in the scene and hence their shape could be found beforehand. It is not obvious which problem should be tackled first. Model-based object recognition systems using feature indexing, which have the advantage of knowing the exact models of objects in the scene, try to identify these objects on the basis of some very specific features first [7]. The model selected on the basis of the identified features is projected onto the image in the hypothesized position and orientation to verify the match [13,23]. In most computer vision systems, however, some higher level local features that alone or in combination correspond to parts or objects are computed first, especially if no a priori known object models are given. These local features or combinations of them can be used either to instantiate an object model from a data base or for further aggregation into shape models of larger granularity. For this proposed work we assume that no models of a priori known objects are given aside from generic models that encompass a large set of all possible part shapes. We believe that in such cases the solution for segmentation might well be to do it *simultaneously* - to recover such parts in the images that can be described with a selected part shape vocabulary.

The close relation of shape recovery and segmentation is reflected in numerous vision systems where a clear distinction between segmentation, shape recovery and model instantiation is difficult to establish. Most approaches to segmentation in computer vision are based on using local image information, in the form of low level image models such as edges, surface patches and surface normals. Segmentation methods can be divided into boundary and region based methods. Boundary methods try to find significant changes that separate regions in images, while region based methods look for similarity which indicates elements that belong together. The simplest region based segmentation methods are 2-D pattern recognition techniques using pixel classification based on the gray-level, color and other local properties. When 3-D data is available, surface normals are a commonly used local feature. Partitioning then involves thresholding using histogram analysis or clustering in multidimensional space when several properties are used simultaneously. Since this features are very local, noise and missing information makes these segmentation methods unreliable. The problem can be partially alleviated by using coherence measures in a somewhat larger neighborhood. Examples are edge tracking and region growing, using consistency criteria for merging and splitting [40]. Fitting of planar or higher order surface patches in a local neighborhood is a popular method to assure local consistency in range maps [18,20,9,19,51]. Some of these methods derive the initial boundaries of local surface patches from edges and significant changes in surfaces expressed in terms of differential geometry [34,8] or discontinuities of surface depth and surface normals [16]. The resulting segmentation is often *arbitrary,* even if the similar neighboring surface patches are later merged, which is especially true for nonpolyhedral objects. This is because merging or growing of such small surface regions essentially still relies on local information. If such local segmentation methods are made sensitive enough to detect subtle changes in first or second derivatives in order to find part boundaries, they become susceptible to noise and details that are not relevant for the targeted level of representation. Such noise problems can sometimes be handled by following up events in a sequence of images at multiple resolutions, such as scale-space [54]. The importance of these multiresolution techniques is that progressive blurring of images clarifies their deep structure [30]. Large scale structure constrains the structure at finer levels so that adding details entails only adding information and does not require changing the larger structure.

Human visual perception has a remarkable capacity to grasp the overall structure of images. We can easily group the relevant features together and find parts without the need to actually recognize them. The systematic study of this perceptual organization phenomenon was first undertaken by the Gestalt school in psychology in the first part of the 20th century [53]. Recently, psychological experiments have shown the particular salience of parts and part configuration as the natural bridge connecting perception (appearance) of objects, behavior (activity) toward them and in turn communication about them (naming) [50]. This *special relevance of parts* is due to their level of representation which reflects the natural breaks in the structure of the world. Research in clinical neurology has shown that the human visual system consists of mutually dissociable functions, such as visual acuity, visual shape disrimination, location and color perception [52]. Of special importance to the proposed work is the dissociation between visual acuity and shape discrimination on one hand and between shape description and recognition on the other hand. Warrington [52] reports that although some patients had normal visual acuity (they were able to read small print) they were unable to differentiate between a square and an oblong. A possible explanation is that this is due to the failure of a special stage in the visual system, a presemantic post-sensory stage that achieves perceptual categorization. On the other hand, some patients failed to recognize objects although it appeared that the patients experienced an adequately-organized percept. Patients could, for example, correctly segment overlapping figures, but could not recognize them. This perceptual categorization stage can therefore aggregate low level features into larger entities or achieve segmentation without semantic knowledge. Investigating part level models that would play a similar role in computer vision is hence justified.

There were several attempts to define parts as perceived by human vision in mathematical terms. Koenderink and van Doorn [31] defined part intersections as parabolic lines on the surfaces of objects. Hoffman and Richards [26] refined the solution by using instead the "negative minima of principal curvatures." The latter definition works better for figure/ground reversal when the perceived parts can change completely. The application of the above partitioning rules on real scenes is difficult because of imperfections in low-level shape descriptions. Since part boundaries are defined in terms of differential geometry, the objects in the scene must be described with smooth surfaces so that second partial derivatives can be computed. Normally, edges and other sharp discontinuities must be smoothed out so that differentiation can be done. Koenderink as well as Hoffman and Richards suggested using contours and occluding contours as an alternative source of information for finding parts, because, from contours, the local surface shape can be inferred. Asada and Brady [3] used a set of images at different scales for segmenting 2-D contours. A 2-D contour is, however, still a locally based shape information and segmentation based solely on it cannot always be consistent. Fischler and Bolles [21] demonstrated that purely mathematical definitions of intrinsic contour structure are not sufficiently selective to duplicate human performance in partitioning because that depends on the purpose. Psychological experiments have also shown that a reasonable amount of noise on occluding contours does not interfere with human capability of recognition [10]. Illusory contours, a well known phenomena in perception, also cannot be explained purely in terms of local image structure.

All local segmentation methods, used so far in computer vision, based whether on surfaces or on contours, have problems with arbitrary segmentation. The cause seems to be that an essentially local piece of information cannot decide on the shape of the whole part if the concept of the whole part as such is not defined.

The problem of using part boundaries to define the shape of parts can be circumvented by directly defining a family of all possible part shapes. Biederman [10] argued that human perception uses a set of primitive building blocks called Geons which can describe the wealth of different shapes by combining them like phonemes in a language. Geons are based on generalized cylinders, the most widespread part level model in computer vision to date [11]. The ACRONYM vision system [17] uses rules to combine 2-D edges that form perceptually relevant entities into general cylinders to get 3-D interpretations of the image. Such perceptual grouping can be used not only to constrain the assembly of low level image models such as edges and corners into models of larger granularity as in the ACRONYM system but also to extract the relevant low level image features and filter out the noise in order to reduce the search space when model matching is performed [32,22].

The predictive power of generic models is not used to its full potential when only rules for combining low level models into larger ones are used. If the higher level generic models are well defined, one can attempt to find them in a more direct way. Rao and Nevatia [41] are finding a subclass of generalized cylinders directly from range images although the search is still partially rule based. Search can be made more efficient if the objective can be defined in purely mathematical terms. An example of such concise definition is symmetry axis transform [12] or one of its variations [15]. Although symmetry axis transform is not a pure shape representation it captures well the shape structure and can serve for decomposition of 2-D shapes of objects into parts [15].

Pentland [36] proposed the use of superquadric models combined with global deformations as a set of primitives which very closely correspond to Hoffman's notion of parts [26] and which could be recovered directly from images. Pentland's initial idea [36] to analytically solve all independent superquadric parameters did not prove to be practical. Pentland later combined part model recovery with segmentation and based it on search through the entire superquadric parameter space, using 3-D points from range images as input [37]. This search is a computationally expensive method. We formulated the recovery of deformed superquadric models from range data as a least-squares minimization of a fitting function [43].

Since the proposed segmentation method is also based on this part recovery method we give a definition of superquadrics and a brief summary of the model recovery method in section 2.1.1. The recovery method can be envisioned as an interaction of intrinsic and extrinsic forces, where the intrinsic forces are the internal properties of the model, governing the arrangement of its parameters and through them its potential shape. The extrinsic forces are the image properties that influence the shape options allowed by the internal constraints. Since only a few model parameters are needed to describe a large number of image points, the model recovery problem is overconstrained. A similar notion of such active models whose shape is a result of internal parametrization and image forces can be found in work of Terzopoulos, Witkin and Kass, either for recovering 3-D shape [47,48], or for recovering 2-D contours in intensity images [29]. Section 2.1.2 summarizes the attempts at part-level segmentation with superquadric models.

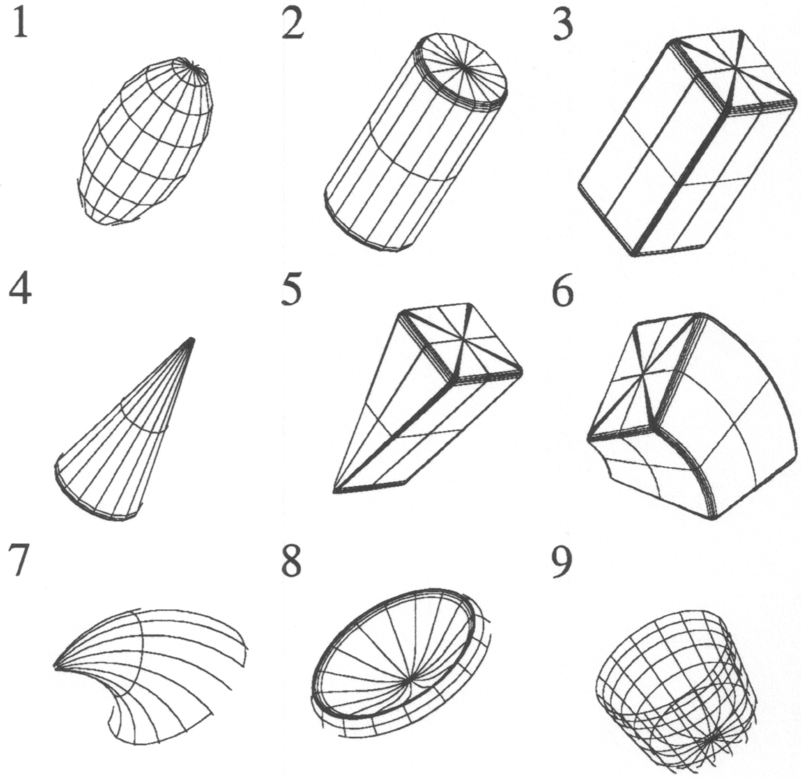

Figure 1. Superquadrics (*1, 2, 3*) and deformed superquadrics (models *4*, and *5* are tapered, model *6* is bent, model *7* is tapered and bent, models *8* and *9* are a result of a cavity deformation).

2.1.1 Superquadrics and their recovery

Superquadrics are an extension of basic quadric surfaces and solids (Figure 1). Superquadrics have been considered as primitives for shape representation in computer graphics [5] and computer vision [36,4,14]. Superquadrics are best to imagine as lumps of clay that can be further deformed and glued together into realistic looking models as is nicely demonstrated by Pentland's *Supersketch* graphics system [36].

Superquadric surface is defined by the following equation

$$F(x,y,z) = \left(\left(\left(\frac{x}{a_1}\right)^{\frac{2}{\epsilon_2}} + \left(\frac{y}{a_2}\right)^{\frac{2}{\epsilon_2}} \right)^{\frac{\epsilon_2}{\epsilon_1}} + \left(\frac{z}{a_3}\right)^{\frac{2}{\epsilon_1}} \right)^{\epsilon_1} . \tag{1}$$

When both ϵ_1 and ϵ_2 are 1, the surface defined is an ellipsoid or, if a_1, a_2, a_3 are all equal, a sphere. When $\epsilon_1 \ll 1$ and $\epsilon_2 = 1$, the superquadric surface is shaped like a cylinder. Parallelepipeds are produced when both $\epsilon_1 \ll 1$ and $\epsilon_2 \ll 1$. Modeling capabilities of superquadrics can be enhanced by deforming them in different ways, such as tapering and bending [43].

The function in equation (1) is called the inside-outside function because it determines where a given point (x, y, z) lies relative to the superquadric surface. The inside-outside function (1) defines the superquadric surface in an object centered coordinate system (x_S, y_S, z_S). To recover a superquadric in general position, an inside-outside function for general position is used where the relation between the image coordinate system and the object centered coordinate system is described with a homogeneous transform $\mathbf{T}$. The inside-outside function for superquadrics in general position is then

$$F(x, y, z) = F(x, y, z; a_1, a_2, a_3, \epsilon_1, \epsilon_2, \phi, \theta, \psi, p_x, p_y, p_z). \tag{2}$$

This expanded inside-outside function has 11 parameters; a_1, a_2, a_3 define the superquadric size; ϵ_1 and ϵ_2 are shape parameters; ϕ, θ, ψ define the orientation in space, and p_x, p_y, p_z define the position in space. We refer to the set of all model parameters as $\Lambda = \{a_1, a_2, \ldots, a_{11}\}$.

For shape recovery of single-part objects we assume that just a single object is present in the range image at a given moment. The range points that represent the supporting surface in the image can be removed from the set of all range points by fitting a plane to the supporting surface and removing all points on or close to that plane. We can safely assume that the remaining range points lie on the surface of the object. Suppose we have N 3-D surface points (x_W, y_W, z_W) which we want to model with a superquadric. We want to vary the 11 parameters $a_j, j = 1, \ldots, 11$ in equation 2 to get such values for a_j's that most of the 3-D points will lie on, or close to the model's surface. There probably does not exist a set of parameters Λ that perfectly fits the data. Finding the model Λ for which the distance from points to the model's surface is minimal is a least-squares minimization problem. Since due to self occlusion, not all sides of an object are visible at the same time, we have to introduce an additional constraint. Among all possible solutions we want to find the *smallest* superquadric that fits the given range points in the least squares sense. We defined the following function which has a minimum corresponding to the smallest superquadric that fits a set of 3-D points *and* a function value for surface points which is known before minimization

$$R = \sqrt{a_1 a_2 a_3}\,(F - 1), \tag{3}$$

Since, for a point (x_W, y_W, z_W) on the surface of a superquadric

$$R(x_W, y_W, z_W; a_1, \ldots, a_{11}) = 0, \tag{4}$$

we have to find

$$G = min \sum_{i=1}^{N} [R(x_{W_1}, y_{W_1}, z_{W_1}; a_1, \ldots, a_{11})]^2. \tag{5}$$

Since R is a nonlinear function of 11 parameters $a_j, j = 1, \ldots, 11$, minimization must proceed iteratively. Using the Levenberg-Marquardt method for nonlinear

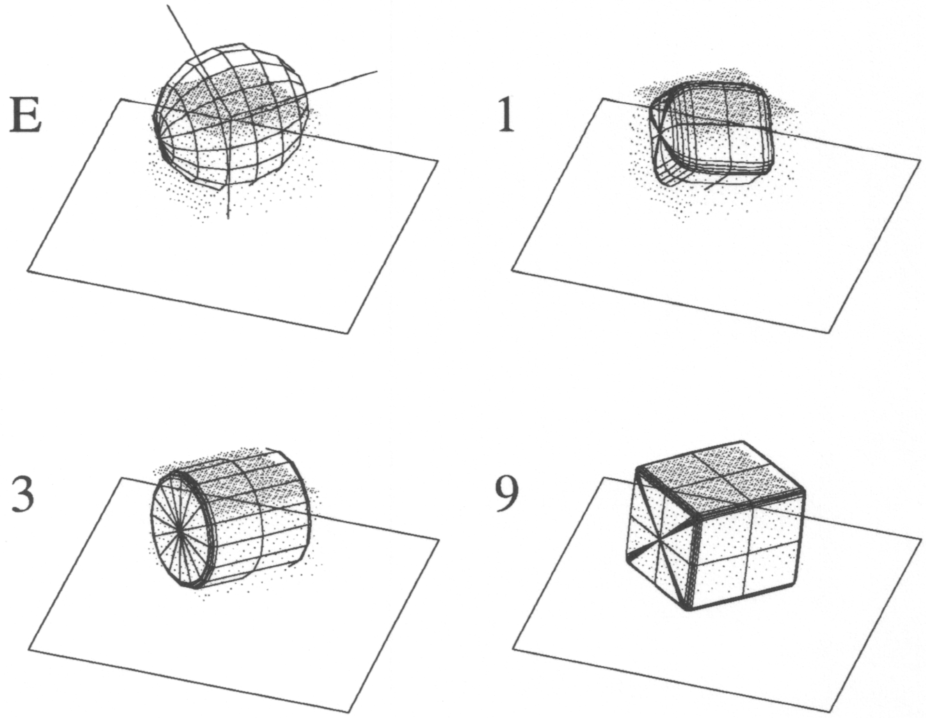

Figure 2. Shape recovery of a parallelepiped-like object. Shown are the initial superquadric model (E) and models after 1st, 3rd, and 9th iteration during the iterative model recovery.

least squares minimization [39] in most cases 15 iterations are more then sufficient (Figure 2). Only very rough initial estimates of object's true position, orientation, and size suffice to assure convergence to a local minimum that corresponds to the actual shape. This is important since these parameters can be estimated only from the range points on the visible side of the object and hence the estimates cannot be very accurate to begin with. Deformed superquadrics can be recovered using the same technique as for the recovery of non-deformed superquadrics. The only difference is that some additional parameters describing deformations must also be recovered. Deformations such as simplified tapering, bending and twisting require just a few additional parameters [6].

Such recovery takes on the order of 20 to 30 seconds on a VAX 785 machine. For details and issues concerning speed, consistency, stability and ambiguity of model recovery see [43].

A similar recovery method using minimization of an analytical fitting function was described by Boult and Gross [14] although shape deformations were not included. The same authors also made a comparison of different fitting functions and found out that there are problems and biases with currently used error of fit measures in special cases. They suggested that better error of fit measures which would utilize knowledge of sensor error models could be found [24].

Pentland [37] took a different approach to recovery of superquadric models alltogether. First, a detailed, nonadaptive search through the entire model parameter space is performed. The selected model is afterwards still adjusted by minimizing an error of fit measure.

2.1.2 Segmentation using superquadric models

Part level segmentation using superquadric models was studied so far by Pentland [37,38] and authors of this proposal [42,43].

Pentland's first attempt at segmentation was based on the recovery method mentioned above [37]. Each region of an image was subjected to this search through the parameter space to find constant regions that could correspond to parts. Stable computation of these properties has proven to be difficult. Pentland [38] suggested instead a new method, based on segmenting first 2-D silhuettes using 2-D projections of 3-D superquadric parts for filtering and matching. He defined a "goodness" measure based on minimal encoding to select the best hypothesis about an object's part structure. When the part structure is resolved in two dimensions 3-D models are fitted to available range measures. Encouraging results are shown, a notable limitation, however, is that silhuettes are the basis for segmentation so that parts internal to the silhuette are lost.

Our attempt at segmentation [42,43] is an extension of the model recovery method described in section 2.1.1. We approached the problem by recursive splitting technique that performs first a fit of an entire object with a single superquadric model, finds areas of high error and refits the model to recover the largest/central part. New models are added to recover other parts in the same way. This is done essentially by adding a new parameter, a threshold **T** into the fitting process. During minimization the quality of each point's fit is measured and compared to **T**. If worse than **T** the data point is discarded from those used to form the estimates of model parameters. In subsequent iterations the discarded points are checked again to see if they fit the new parameters to re-include them into the model. We obtained good results in simple situations (2-part objects) but the method is quite dependent upon the starting point and threshold **T**, although the threshold adapts as a function of the overall goodness of fit. Another problem is the serial nature of the recovery procedure, where only a part is recovered at a time. In particular, we were not happy with the thresholding method for deciding whether a given range point should be incorporated into the model or not.

2.2 Proposed Work

We want to further pursue superquadric recovery methods using analytical error of fit measures for segmentation and for using beside 3-D data points other types of visual information such as contours and surface orientation. We believe that this possibility of using analytic methods is a major advantage of superquadric parametric models in comparison to other 3-D volumetric models. In this way powerfull standard minimization techniques can be used.

2.2.1 Design

For segmentation we intend to find instead of using a threshold a better criterion of splitting objects into parts. One direction we want to investigate is the robustization of least-squares by pulling outliers towards their fitted values [27] or by changing the fitting functional in such a way that the influence of points lying far from the model will recede with the distance.

Another direction we want to follow is to use a separate term in the fitting functional which represents a cost measure of introducing discontinuities. Such methods are known from fitting surfaces to depth data.

The serial manner of segmentation we used so far cannot exploit the coherence of physical objects. If a data point does not belong to a part, it has to belong to some other part. Shape recovery of neighboring parts should influence each other. Knowledge about structure can be represented also by part to part constraints, such as how parts can touch and whether they can interpenetrate each other. A mathematically concise way of describing such constraints, including external constraints such as gravity, is in terms of energy [55]. Such constraints could be incorporated into the described recovery method quite easily since they would only add additional terms into the functional that has to be minimized. A parallel scheme where several part recovery processes could *cooperate* in the image simultaneously is essential. The role of recursive decomposition, however, when smaller parts are added to larger ones only if scale or attention is focused upon them is not to be neglected.

In parallel to the work on segmentation we want to investigate new error of fit measures for recovery of 3-D superquadric models from information sources other than 3-D points. We made some initial tests in using surface normal data along with 3-D points for superquadric recovery [4]. Using more then one shape cue can improve the shape recovery of part models which are at the same time a convenient way of integrating information from different cues. We want to find out if 3-D superquadric models could be recovered from 2-D contours (up to a scaling factor) with analytical methods. Human perception is very good at interpreting contours and we believe that the built-in parametrization of superquadrics can provide enough constraints to the recovery problem so that unique or at most two solutions would result (i.e. two competing intepretations of the Necker cube).

Between the problem of working with 2-D contours only and having accurate 3-D positions of points is a whole range of situations where the depth information is less accurate then the x-y position of contours in the image plane. This is actually what human perception has to content with. Depth information is often more qualitative then quantitative in the sense that we have the information about the relative distances of points, for example, which points are closer or further away from the observer. This is normally sufficient to select the correct interpretation out of several possible interpretations of 2-D contour information alone. The situation in computer vision is very much the same. Due to the imaging sensors one normally has higher resolution in image plane then in the z (depth) direction. A way of incorporating this inherent asymmetry of position uncertainty into superquadric model recovery must be found. We want to define a part-based shape recovery procedure that could deal with the whole range of possibilities, from having 2-D contours only, up to accurate depth information and situations in between. Insights from recent general framework for information fusion from different sensors and for sensor modeling [25] will be used to do that.

We would like to emphasize the importance of working with 3-D models and making 3-D interpretations as early as possible for part-level shape description. Any 2-D stimulus pattern tends to be seen in such a way that the resulting 3-D structure is as simple as the given conditions permit [2]. For example, a pattern will appear three-dimensional when it can be seen as the projection of three-dimensional situation which is structurally simpler than the two-dimensional pattern. Skewed symmetry as a manifestation of this principle was investigated in computer vision [28]. Using 3-D superquadric models for segmentation and recovery and not only their 2-D projections as Pentland [38] does is hence of great importance to recover the simplest interpretation.

2.2.2 Implementation

The code will be written in C for easy portability under Macintosh Finder system or under Apple Unix.

2.2.3 Evaluation

Different data sources will be used for testing and evaluation. We want to emphasize especially different types of depth and/or orientation data; range data, 2-D contours, shading, stereo and color. Part-level segmentation results will be compared with common bottom-up segmentation techniques.

2.3 Impact of Proposed Work

The results of the proposed work should have impact on some basic issues in vision research, especially on the role of shape models in scene interpretation and understanding. Some of the important questions that might be better understood are whether models in vision should be mostly prescriptive or descriptive and how to perform the translation from signals to symbols in computer vision.

Results of this work should be also direclty applicable to various problems in industrial vision (object handling) and robotics in general (visual navigation, object avoidance).

3 Resources and organization of work

3.1 Personnel

Dr. Franc Solina, assistant professor of computer science at Ljubljana University will be the principal investigator on the Yugoslav side. Dr. Solina spent five years as a Ph.D. student and a post-doctoral fellow in General Robotics and Active Sensory Perception Laboratory at University of Pennsylvania where Prof. Ruzena Bacsy, the US co-principal investigator, was his Ph.D. advisor. They worked on problems of shape representation and published several joint papers, most of them listed in the references. Graduate students, funded primarily from other sources (Slovenian Research Council), will assist Dr. Solina in Ljubljana.

Prof. Bajcsy who is also the director of the GRASP Laboratory has several graduate students and research associates that work on similar computer vision problems and who will get involved when necessary.

3.2 Benefits

The proposed project should enable both parties to continue their long and sucessfull cooperation and finish some of the problems that remained open when Dr. Solina left USA to teach at Ljubljana University. The results of the described joint work include so far two journal publications [46,45] and several conference papers. In particular, the funding of this project would enable Dr. Solina to follow and participate in current computer vision research in US, the country with the largest concentration of vision researchers and at the same time influence the level of computer vision research in Yugoslavia. Also beneficial to research in Yugoslavia would be visits of American researchers in Yugoslavia that would result from this cooperation.

On the other hand, there are several ongoing research projects in computer vision and robotics in the General Robotics and Active Sensory Perception funded by American governmental agencies and private industry that could benefit from the results of the proposed project.

3.3 Facilities

Research on the Yugoslav side will be performed primarily on Macintosh II computers equiped with color graphics and a LaserWriter II. Since electronic mail connection to the GRASP Laboratory at University of Pennsylvania is established, regular contacts and exchange of images and software is possible.

The facilities for vision research at the Computer and Information Science Department at University of Pennsylvania are extensive and of great importance for the proposed work. Of special importance to this proposal is a laser scanner for taking range images of objects and parallel computers (Connection machine) for studying possible speed-up of newly developed algorithms and methods achivable on parallel machines.

3.3.1 Justification of equipment purchase

Since access to a Macintosh II computer for the purpose of this project is limited, the funding of this proposal would enable the purchase of another Macintosh II computer with Unix operating system devoted entirely to this project. Macintosh II series of computers represent a cost effective entry into personal work stations. Because of their excellent graphic environment and our experience with this kind of equipment, we judge them to be the most suitable for our planned research in computer vision.

In the first year of the proposed project we plan the purchase of a Macintosh II computer (80Mb hard disk, 5Mb RAM) with Apple Unix and an ethernet card to connect it to the existing network at the Faculty of electrical engineering and computer science. In the second year, a purchase of an image graber for Mac II and a CCD video camera would follow for image entry on site.

This plan of equipment purchase would neccesitate a somewhat larger budget in the first year, however the overall three-year project budget would not exceed the suggested funding limit.

3.4 Organization and time plan

The largest part of the proposed work will be done in Ljubljana while some of the experiments and testing will be performed at University of Pennsylvania where the necessary equipment is readily available. For longer stays (summer visits up to a few moths) of Yugoslav scientists participating on this project, additional funding will be made available by the American partner. The funding of this project will enable most of all to cover the international transportation costs which are difficult to pay for from other sources.

Regular contacts, daily if necessary, are possible over electronic mail for exchange of ideas and for transfer of data files. Visits by both parties will be used for more detailed discussions and will be planned around possible presentations of joint papers at conferences.

The proposed lenght of the project is three years. In the first year the model recovery of single part objects from various types of data will be studied. The subsequent two years will be devoted to the segmentation issue. First simple articulated objects consisting of a few parts will be studied, later entire scenes will be attempted.

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Experience:

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Jan.–Aug. 1988 **Postdoctoral Fellow**, University of Pennsylvania
Research in computer vision in General Robotics and Active Sensory Perception Laboratory. Worked on interpretation of range images of mail pieces under a US Postal Service contract. Participated and gave talks at DARPA Image Understanding/Strategic Computing review meetings (Autonomous Land Vehicle Project).

1984 – 87 **Graduate student**, CIS Department, University of Pennsylvania.
Worked as teaching and research assistant. Introduced a method for recovery of compact volumetric models (superquadrics with deformations) for shape representation and segmentation. Studied quantization errors in stereo vision.

1983 – 84 **Visiting Researcher**, CIS Department, University of Pennsylvania.
Work on shape representation for computer vision. Supported by the Fulbright program and the International Research and Exchange Board, New York.

1982 – 83 **Programmer**, Hydrographic Institute of the Yugoslav Navy.
During one year mandatory army service assigned to the computer center of the Navy Hydrographic Institute in Split, Yugoslavia.

1979 – 82 **Research Assistant**, University of Ljubljana.
Worked on computer analysis of biological signals in the Laboratory for systems, automatics and cybernetics. Supported by a Fellowship from the Slovenian Research Council.

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Reviewer: IEEE Pattern Analysis and Machine Intelligence Journal,
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Professional Experience

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Teaching and Research Experience

1956-1957	Instructor, Department of Mathematics, Slovak Technical University, Bratislava, Czechoslovakia.
1964-1967	Assistant Professor, Department of Computer Science, Slovak Technical University, Bratislava, Czechoslovakia.
1967-1968	Research Assistant, Artificial Intelligence Project, Stanford University, Stanford, California.
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1972-1977	Assistant Professor, Department of Computer and Information Science, University of Pennsylvania, Philadelphia.
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- Graduate Fellowship for study at Stanford University, October 1967–January 1972.
- Research Fellowship Pattern Recognition Group, CERN, Geneva, January–May 1975. (Because of my immigration status, I was not able to accept it at that time).
- Visiting scientist at INRIA-FRANCE, January–June 1979.
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3. "Three-Dimensional Scene Analysis", in *Pattern Recognition Theory and Applications,* (Proceedings of NATO ASI, St. Anne's College, Oxford, 29 March-10 April 1981), D. Reidel Publishing Co., eds.: J. Kittler, K. S. Fu and L. Pau.

4. "Computerized Anatomy Atlas", in *Pattern Recognition Theory and Applications,* (Proceedings of NATO ASI, St. Anne's College, Oxford, 29 March-10 April 1981), D. Reidel Publishing Co., eds.: J. Kittler, K. S. Fu and L. Pau, (Co-authors: P. Karp and A. Stein).

5. "Segmentation of Tomographic Images", in *Biomedical Image Processing* (Proceedings of the United States-France Seminar, May 1980), eds.: J. Sklansky and J. C. Bisconte, Springer-Verlag, New York, 1981.

6. "Integrating Vision and Touch for Robotics Applications", in:*Trends and Applications of AI in Business* (ed. W. Reitman), Ablex Publ. Co, 1984.

7. "Shape from Touch", in *Advances in Automation and Robotics, Theory and Application,* (ed.: G. Saridis) Vol. 1, Summer 1984, JAI Press Inc.

8. "Parallels Between Vision and Touch", in *Vision, Brain and Cooperative Computation* (ed.: M. A. Arbib and A. R. Hanson), 1984.

9. "Three-Dimensional Analysis and Display of Medical Images", in *Positron Emission Tomography* (eds.: M. Reivich and Abass Alavi), Alan R. Liss, Inc., Scientific, Medical and Scholarly Publ., N.Y., 1984.

10. "What can we learn from one finger experiments?" In M. Brady and R. Paul (Eds.), *The First International Symposium on Robotics Research.* Cambridge, MA: The MIT Press, 1984.

11. "Integrating Vision and Touch for Grasping of an Object", in *Computer-Based Automation* (ed.: Julius Tou), Plenum Publishing Corp., 1985, pp. 387-398.

12. "Converging Disparate Sensory Data," Proceedings of the 2nd International Symposium on Robotics Research, (ed. Hanafusa and Inoue) MIT Press, 1985, pp. 81-87, (Co-author: P. Allen).

13. "Multisensor Integration", *Encyclopedia of Artificial Intelligence*, John Wiley & Sons, Publ., 1986.

14. "Tactile Information Processing", *Pyramidal Systems for Computer Vision*, V. Cantoni and S. Levialdi, NATO ASI Series, Series F: Computer and Systems Sciences, Vol. 25, Springer Verlag, 1986.

15. "Two Sensors Are Better Than One: Example of Integration of Vision and Touch", *Robotics Research: the Third International Symposium*, (eds: O. Faugeras and G. Giralt), MIT Press, 1986, pp. 59-64.

16. "Models of Errors and Mistakes in Machine Perception - Part 1. First Results for Computer Vision Range Measurements", NATO ASI Series, Series F: Computer and Systems Sciences, Vol. 43, Springer Verlag, 1987 (Co-authors: Eric Krotkov and Max Mintz).

17. "Perception via Manipulation", Proceedings of the Fourth International Symposium of Robotics Research, (edited by R. Bolles and B. Roth), MIT Press, August 1987.

18. "Segmentation versus object representation – are they separable?" (Co-authors: Franc Solina and Alok Gupta), Presented at the Range Image Understanding Workshop, March 21-23, 1988. (To appear as a Book Chapter: ed. Ramesh Jain, Springer Verlag).

Conference Proceedings

1. "Computer Texture Analysis", Proceedings of the 3rd Hawaii International Conference on System Science, Hawaii, 1970.

2. "Computer Description of Textured Surfaces", Proceedings of IJCAI, 1973, Stanford.

3. "Computer Recognition of Bridges, Rivers and Lakes", Proceedings of Conference on Machine Processing Remotely Sensed Data, 1973, Purdue, (Co-author: M. Tavakoli)

4. "Computer Description of Real Outdoor Scenes", Proceedings of Conference on the and International Pattern Recognition Conference, Copenhagen, 1974 (Co-author: L. Lieberman)

5. "Computer Recognition of Roads from Satellite Pictures", Proceedings of the 2nd International Pattern Recognition Conference, Copenhagen, 1974 (Co-author: M. Tavakoli)

6. "A Computational Structure for Color Perception", Proceedings of the ACM Conference, Minnesota, 1975 (Co-author: K. Sloan)

7. "Visual Focussing and Defocussing–An Essential Part of Pattern Recognition Process" Proceedings of Computer Graphics Pattern Recognition and Data Structure Conference, Los Angeles, 1975 (Co-author: P. Chance)

8. "Computer Description of Real Outdoor Scenes", IEEE Computer Society Workshop on Data Structures and Pattern Recognition, Albequerque, New Mexico, February 1976.

9. "Regular Repetitive Pattern–A Texture Problem", Algorithms for Image Processing, New Hampshire, August 1976.

10. “Three Dimensional Reconstruction from Serial Sections”, New Vistas of Optical Pattern Recognition, Philadelphia, PA, August 1976 (Co-author: B. Soroka).

11. “Computer Description of Regular Patterns Found on Potsherds”, The Milwaukee Symposium on Automatic Computation and Control, 1976 (Co-author: J.M. Epstein).

12. “Artificial Intelligence Techniques in Processing of Satellite Pictures”, Proceedings of the 7th Annual Pittsburgh Conference on Modelling and Simulation, Pittsburgh, 1976.

13. “Aerial Perspective–Monocular Depth Cue for Landscape Scenes”, Digest from Joint Workshop on Pattern Recognition and Artificial Intelligence, Hyannis, Cape Cod, MA 1976 (Co-authors: N. Friedman and K. Sloan).

14. “Generalized Cylinders from Serial Sections, 3rd International Pattern Recognition Conference, San Diego, California, 1976 (Co-author: B. Soroka).

15. “Artificial Intelligence Techniques in Processing of Satellite Pictures”, Kouferenze Berichte-Luftfahrt-Raumfahrt-Weltraumforsching, 1976.

16. “World-Model-Driven Recognition of Natural Scenes”, IEEE Workshop on Picture Data Description and Management, Chicago, April 20-22, 1977 (Co-author: K. Sloan).

17. “What Can One See on the Earth from Different Altitudes–A Hierarchical Control Structure” 1977 Pattern Recognition and Image Processing, 1977, Troy, New York, June 6-8.

18. “Steps Towards the Representation of Complex Three-Dimensional Objects”, Proceedings of the 3rd IJCAI Conference, Boston, August 1977 (Co-author: B. Soroka).

19. “A Computer System for Reconstruction and Display of the Macrostructure of the Brain from Radiographs of Serial Sections”, Biosigma 78, Paris, April 1978 (Co-author: I. Winston).

20. “A Program for Describing Complex Three-Dimensional Objects Using Generalized Cylinders as Primitives”, Proceedings IEEE Pattern Recognition and Image Processing Conference 331-339, Chicago, June 1978 (Co-author: B. Soroka).

21. “The Problem of Naming Shapes: Vision-Language Interface”, TINLAP-2, Urbana-Champaign, Illinois, July 1978 (Co-author: A.K.. Joshi).

22. “A Computer Analysis and Description of Pottery Sherd Patterns”, Proceedings IEEE Pattern Recognition and Image Processing Conference, Chicago, June 1978.

23. “Segmentation of Tomographic Images”, Presented at the US/France Seminar on Biomedical Image Processing, May 1980.

24. “Computerized Anatomy Atlas”, Proceedings of Conference of Picture Processing and Data Structure, Monterey, California, August, 1980 (Co-authors: A. Stein, P. Karp).

25. “Three-Dimensional Scene Analysis”, invited paper at the International Pattern Recognition Conference, Published in the Proceedings of the Conference, Miami, December 1980.

26. “Three-Dimensional Scene Analysis”, invited paper at the International Pattern Recognition Conference, Published in the Proceedings of the Conference, Miami, December 1980.

27. “Three-Dimensional Reconstruction of Objects from Incomplete Data and A Priori Knowledge”, Proceedings IPR, Miami Beach, December 1980 (Co-author: C. Tsikos).

28. “Computerized Anatomy Atlas of the Human Brain”, Proceedings of the SPIE Conference, Washington, D.C. April 1981.

29. “Detecting Moving Objects in Low Resolution Infrared Images”, Proceedings of the Canadian Man-Machine Conference, Toronto, Canada, June 1981.

30. "A Three-Dimensional Object-Centered Model Builder", Proceedings of the 6th IPR, Munich 1982 (Co-author: C. Dane).

31. "Matching of Deformed Images", Proceedings of the 6th IAPR, Munich 1982 (Co-author: C.H. Broit).

32. "What Can We Learn From One-Finger Experiments", Presented at U.S.-France Seminar in Robotics, Paris, May 1982.

33. "SCIMR–A Test Bed for Real Time Processing of Sensory Data", Proceedings of the PRIP Conference, Las Vegas, June 1982 (Co-author: R.L.Anderson).

34. "When is an Object Stable and Balanced", Proceedings of the PRIP Conference, 583-686, Las Vegas, June 1982.

35. "3-D Representation of Objects", Marr Conference, Cold Spring Harbor, April 26-29, 1983.

36. "A Distributed Active Sensory Processing System", presented at the Third Scandinavian Conference on Image Analysis, Copenhagen, Denmark, July 12-14, 1983.

37. "Sensing Strategies", presented at the 2nd ISRR, Tokyo, Japan, August 1984, (Co-author: P. Allen).

38. "Stereo Processing of Aerial Images", Proceedings of the 7th Intl. Pattern Design Conference, Montreal, August 1984 (Co-author: David Smitley).

39. "Feeling by Grasping," Proceedings of the IEEE International Conference on Robotics, Atlanta, 13-15 March 1984, pp. 461-467.

40. "Tactile Information Processing-The Bottom Up Approach", Proceedings of the 7th International Conference on Pattern Recognition, Vol. 2, Montreal, 30 July - 2 August 1984, pp. 809-813.

41. "Three Dimensional Elastic Matching of Ventricles", Proceedings of the 6th Annual Conference on the Computer Graphics Association, Vol. III, 14-18, April 1985, Dallas, TX, pp. 206-214.

42. "Integrated Visual and tactile Sensory Processing Systems: The Peak and Poke Approach", presented at IEEE International Conference on Computer Design: VLSI in Computers, rye Brook, NY 7-10 October 1985.

43. "Active Perception vs. Passive Perception", presented at the IEEE Computer Society Third Workshop on Computer Vision: Representation and Control, Bellaire, MI, October 13-16, 1985, pp. 55-59.

44. "LandScan: A Natural Language and Computer Vision System for Analyzing Aerial Images," *Proceedings of IJCAI 1985*, vol. 2, pp. 919-922, (Co-authors: A. Joshi, E. Krotkov, A. Zwarico).

45. "Object Recognition Using Vision and Touch", IJCAI 1984 vol. 2, pp. 1131-1137 (Co-author: P. Allen).

46. "Active Versus Passive Vision", Proceedings of the Workshop on Knowledge Representation and Control in Vision, October 14-15, 1985, Michigan.

47. "Models of Errors and Mistakes in Machine Perception", presented at the NATO Conference on Sensors, Maratea, Italy, April 28 to May 3, 1986 (Co-authors: Eric Krotkov and Max Mintz).

48. "Tactile Information Processing," Proceedings of the NATO ARW on Pyramidal Systems for Image Processing and Computer Vision, Maratea, Italy, May 1986 (S. Stansfield).

49. "A Common Framework for Edge Detection and Region Growing", presented at the Eighth International Conference on Pattern Recognition, Paris, France, October 28-31, 1986 (Co-authors: Max Mintz and Erica Liebman).

50. "Modelling of Mail Pieces with Superquadrics," Proceedings USPS Advanced Technology Conference, Washington, D.C., pp. 472-481, 1986 (Co-author: F. Solina).

51. "Shape and Function," SPIE Proceedings, Vol.726, Intelligent Robots and Computer Vision, Cambridge, MA, pp. 284-290, October (1986), (Co-author: F. Solina).

52. "Object Exploration in One and Two Fingered Robots", Proceedings of 1987 IEEE International Conference on Robotics and Automation, March 31 - April 3, 1987, Raleigh, North Carolina (Co-authors: R.L. Klatzky and S.J. Lederman).

53. "Range Image Interpretation of Mail Pieces with Superquadrics," Proceedings AAAI 1987, Seattle, WA, pp. 733-737, July , 1987 (Co-author: F. Solina).

54. "Object Apprehension Using Vision and Touch," Proceedings of the JPL/NASA Space Telerobotics Workshop, Pasadena, Ca., January 1987, (Co-author: S. Stansfield).

55. "Models of Errors and Mistakes in Machine Perception - Part 1. First Results for Computer Vision Range Measurements", presented at DARPA Image Understanding Workshop, Los Angeles, California, February 23-25, 1987 (co-author: Eric Krotkov and Max Mintz).

56. "An Integrated Robotic Sensory System," in Proceedings of the IEEE International Symposium on Circuits and Systems, Philadelphia, PA, May 1987 (Co-Author: S. Stansfield).

57. "Three Dimensional Object Representation Revisited", Proceedings of the First International Conference on Computer Vision, London, England, June 1987. (Co-author: Franc Solina).

58. "Physical Scene Segmentation via Vision and Manipulation", Proceedings of the Third Advanced Technology Conference, Washington, D.C., May 3-5, 1988 (Co-author: C. Tsikos).

59. "Redundant Multi-Modal Interaction of Machine Vision and Programmable Mechanical Manipulation for Scene Segmentation", (NATO ARW on Robots with Redundancy, Antol K. Bejczy (editor), (Co-author: C. Tsikos) Verona, Italy, June 27-30, 1988.

60. "Three-dimensional computerized brain atlas for elastic matching: creation and initial evaluation", SPIE Proceedings, Medical Imaging II, Newport Beach, CA., (Co-authors: Dann R., Hoford J., Kovacic S., Reivich M.) 1988.

61. "A Medium-Complexity Compliant End Effector", (Co-authors: Nathan Ulrich and Richard Paul), 1988 IEEE Conference on Robotics and Automation, Philadelphia, PA.

62. "How do robots take two parts apart?", NASA Conference on Space Telerobotics, to appear (Co-author: C. Tsikos).

63. "Assembly via Disassembly: A Case in Machine Perceptual Development", (Co-author: C. J. Tsikos), Proceedings of the Fifth ISRR, Tokyo, Japan, August 1989.

64. "Active Perception and Exploratory Robotics", 5th International conference on Artificial Intelligence and Information-Control systems of Robots, Czechoslavakia, November 1989 (invited paper).

Editorial Boards

- Co-editor of special issue of *Computer Vision, Graphics, and Image Processing*, 1980.
- Associate Editor of *Trans. of IEEE on Pattern Analysis and Machine Intelligence*, since 1981.
- Editor of the *Newsletter of the International Association for Pattern Recognition* 1981-1984.
- Associate Editor of the *Computer Graphics and Image Processing Journal* since 1983.
- Associate Editor of the *Pattern Recognition Letters* since 1983.
- Associate Editor of *Journal of Robotic Systems* since 1983.
- Associate Editor of *Journal of Computer Vision* since 1986.
- Area Editor of *CVGIP: Image Understanding* since 1989.

Conference Chairs

- Co-chairman of PRIP–Chicago, 1979.
- Publicity chairman of the International Pattern Recognition Conference, 1980.
- Session chairman on the International Pattern Recognition Conference, Munich, 1980 and 1982.
- Invited session chair, "Edge Detection", IEEE Workshop on Computer Vision, Miami, Florida, November 30 - December 2, 1987.
- Chairman, Review Committee for Undergraduate Programs in Computer Science, Loyola University, March 1988
- Chairman, Review Committee for Undergraduate Programs in Computer Science, Tulane University, March 1988
- Co-Chair, Second International Conference Computer Vision, December 5-8, Tarpon Springs, Florida, 1988.
- Invited session chair, "Edge Detection," IEEE Workshop on Computer Vision, Miami, Florida, November 30 - December 2, 1987.

Invited Speaker

- Invited speaker at the Optical Society Meeting in Orlando, December 1981.
- Invited speaker at Data Processing Management Association Regional Conference, Allentown, PA, 13 May 1983, on "Machine Recognition of Shapes from Vision and Touch".
- Invited speaker at The 1983 NYU Symposium on Artificial Intelligence for Business, New York University, 18-20 May 1983 on "Integrating Vision and Touch for Robotics Applications."
- Invited speaker at Seminar and Workshop on Sensors for Robotics and Flexible Automation, University of Rhode Island, Kingston, RI, 8-9 June 1983 on "Shape From Touch".
- Invited speaker, Distinguished Lecturer Series, University of Minnesota, Spring 1986, Computer Science. "Active Perception vs Passive Perception", and "Integration of Vision and Touch for Recognition Purposes".

- Invited speaker, JPL/NASA Space Telerobotics Workshop, "Object Apprehension Using Vision and Touch", Pasadena, California, 1987.
- Invited speaker, AI '87 Japan Conference. "Active Perception", pp. 549-554 .
- Invited speaker, Processing of Somatosensory Information in Biological and Artificial Systems, American Academy of Arts & Sciences, MIT March 27-28, 1989.
- Invited speaker, Sensor Fusion II: Human and Machine Strategies, SPIE, Advances in Intelligent Robotic Systems Symposium, November 6-8, 1989.

Invited Participant

- Invited participant, Research Initiation Grant Program Panel Review, National Science Foundation, March 8-9, 1983.
- Invited Participant, Congressional Office of Technology Assessment Workshop, Committee on Appropriations, United States Senate March 18-19, 1984.
- Invited participant, Engineering Equipment Awards Panel, National Science Foundation, March 26, 1986.
- Invited participant, NATO Advanced Research Workshop on "Robots and Biological Systems", Il Ciocco, Tuscany, Italy, June 26 -30, 1989.
- Invited participant, NATO Advance Study Institute (ASI) on Active Perception and Vision, July 16-19, 1989, Maratea, Italy.

  item Invite participant, NATO Closing Workshop - Sensory Systems for Robotic Control, October 30 - November 3, 1989, Il Ciocco, Tuscany, Italy.

Other Activities

- Organizer of an NSF-Sponsored Workshop on the Representation of Three-Dimensional Objects, University of Pennsylvania, May 1-2, 1979.
- Member of the organizing committee of the Int. Medical Image Processing Conference, Berlin, October 1982.
- Organized the NSF sponsored Joint United States-France Second Workshop on Selected Topics in Robotics, 7-9 November 1984, University of Pennsylvania, Philadelphia, PA.
- Consultant, Advisory Committee, National Science Foundation, May 1, 1985 to April 4, 1986.
- Member of Program Committee, IJCAI '85, 18-23 August 1985, Los Angeles, CA.
- Panel Member, Panel for Manufacturing Engineering, Commission on Physical Sciences, Mathematics, and Resources, National Research Council, 1986 - 1989.
- Member, Advisory Committee for Design, Manufacturing, and Computer-Integrated Engineering for the National Science Foundation, January 1987 - December 1989.
- Program Committee Member, Topical Meeting on Image Understanding and Machine Vision, June 12-14, 1989, Cape Cod, Massachusetts.
- Member, Advisory Committee for the CISE Office of Cross-Disciplinary Activities (CDA), 1989.
- Panel Member, National Defense Science and Engineering Graduate Fellowship Program Evaluation Panel, March, 1989.

PROPOSED BUDGET

1st year of a three year project

Organization	*Duration*	*Start date*
Faculty of electrical engineering and computer science University of Ljubljana	1 year	Jun-90

Principal Investigator/Project Director — ***Franc Solina***

	Funds requested	
	Din eqv. of $	*US$*
A. Senior Personnel (Yugoslav)		
1. Franc Solina	$1,000	$1,000
B. Other Personnel		
1. Two graduate students	$500	$500
C. TOTAL SALARIES AND WAGES (A + B)	$1,500	$1,500
D. Permanent Equipment (Macintosh II computer configuration)	$8,000	$8,000
E. Minor Instrument Components and Spare Parts		
F. TOTAL EQUIPMENT AND SPARE PARTS (D + E)	$8,000	$8,000
G. Domestic Travel	$500	
H. International Travel (Subtotal H.a + b)	$500	$3,000
a) Yugoslav Scientist		
1. Transportation	$500	$1,000
2. Per Diem (US$)		$1,000
b) US Scientist (Transportation, Per Diem, Misc.)		$1,000
I. TOTAL TRAVEL (G + H)	$1,000	$3,000
J. Other Direct Costs		
1. Expendable Materials $ Supplies	$500	$250
2. Publication Costs/Page Charges		
3. Consultant Services		
4. Computer Services		
5. Other (Conference registration)		$250
K. TOTAL OTHER DIRECT COSTS (J.1-5)	$500	$500
L. TOTAL DIRECT COSTS (C + F + I + K)	$11,000	$13,000
M. INDIRECT COSTS (20% of direct costs incurred in dinars, exluding items G. H $ I)	$2,000	
N. GRAND TOTAL (L + M)	$13,000	$13,000

P. I. Signature — 18-Jul-89 *Date*

Institutional Representative Signature — 18-Jul-89 *Date*

PROPOSED BUDGET

2nd year of a three year project

Organization	*Duration*	*Start date*
Faculty of electrical engineering and computer science	1 year	Jun-91
University of Ljubljana		

Principal Investigator/Project Director	***Franc Solina***

	Funds requested	
	Din eqv. of $	*US$*
A. Senior Personnel (Yugoslav)		
1. Franc Solina	$1,000	$1,000
B. Other Personnel		
1. Two graduate students	$500	$500
C. TOTAL SALARIES AND WAGES (A + B)	$1,500	$1,500
D. Permanent Equipment (CCD video camera and digitizer board)	$2,500	$2,500
E. Minor Instrument Components and Spare Parts		
F. TOTAL EQUIPMENT AND SPARE PARTS (D + E)	$2,500	$2,500
G. Domestic Travel	$500	
H. International Travel (Subtotal H.a + b)	$1,000	$2,500
a) Yugoslav Scientist		
1. Transportation	$1,000	$750
2. Per Diem (US$)		$750
b) US Scientist (Transportation, Per Diem, Misc.)		$1,000
I. TOTAL TRAVEL (G + H)	$1,500	$2,500
J. Other Direct Costs		
1. Expendable Materials $ Supplies	$500	$250
2. Publication Costs/Page Charges		
3. Consultant Services	$500	$250
4. Computer Services		
5. Other (Conference registration)		$500
K. TOTAL OTHER DIRECT COSTS (J.1-5)	$1,000	$1,000
L. TOTAL DIRECT COSTS (C + F + I + K)	$6,500	$7,500
M. INDIRECT COSTS		
(20% of direct costs incurred in dinars, exluding items G. H $ I)	$1,000	
N. GRAND TOTAL (L + M)	$7,500	$7,500

	18-Jul-89
P. I. Signature	*Date*

	18-Jul-89
Institutional Representative Signature	*Date*

PROPOSED BUDGET

3rd year of a three year project

Organization	*Duration*	*Start date*
Faculty of electrical engineering and computer science	1 year	Jun-91
University of Ljubljana		

Principal Investigator/Project Director — ***Franc Solina***

	Funds requested	
	Din eqv. of $	*US$*
A. Senior Personnel (Yugoslav)		
1. Franc Solina	$1,000	$1,000
B. Other Personnel		
1. Two graduate students	$500	$500
C. TOTAL SALARIES AND WAGES (A + B)	$1,500	$1,500
D. Permanent Equipment		
E. Minor Instrument Components and Spare Parts	$500	$500
F. TOTAL EQUIPMENT AND SPARE PARTS (D + E)	$500	$500
G. Domestic Travel	$500	
H. International Travel (Subtotal H.a + b)	$1,500	$2,500
a) Yugoslav Scientist		
1. Transportation	$1,500	$750
2. Per Diem (US$)		$750
b) US Scientist (Transportation, Per Diem, Misc.)		$1,000
I. TOTAL TRAVEL (G + H)	$2,000	$2,500
J. Other Direct Costs		
1. Expendable Materials $ Supplies	$500	$250
2. Publication Costs/Page Charges		
3. Consultant Services		
4. Computer Services		
5. Other (Conference registration)		$250
K. TOTAL OTHER DIRECT COSTS (J.1-5)	$500	$500
L. TOTAL DIRECT COSTS (C + F + I + K)	$4,500	$5,000
M. INDIRECT COSTS		
(20% of direct costs incurred in dinars, exluding items G. H $ I)	$500	
N. GRAND TOTAL (L + M)	$5,000	$5,000

P. I. Signature — 18-Jul-89 *Date*

Institutional Representative Signature — 18-Jul-89 *Date*

PROPOSED BUDGET

cumulative for a three year project

Organization	*Duration*	*Start date*
Faculty of electrical engineering and computer science ***University of Ljubljana***	1 year	Jun-91

Principal Investigator/Project Director — ***Franc Solina***

	Funds requested *Din eqv. of $*	*US$*
A. Senior Personnel (Yugoslav)		
1. Franc Solina	$3,000	$3,000
B. Other Personnel		
1. Two graduate students	$1,500	$1,500
C. TOTAL SALARIES AND WAGES (A + B)	$4,500	$4,500
D. Permanent Equipment	$10,500	$10,500
E. Minor Instrument Components and Spare Parts	$500	$500
F. TOTAL EQUIPMENT AND SPARE PARTS (D + E)	$11,000	$11,000
G. Domestic Travel	$1,500	
H. International Travel (Subtotal H.a + b)	$3,000	$8,000
a) Yugoslav Scientist		
1. Transportation	$3,000	$2,500
2. Per Diem (US$)		$2,500
b) US Scientist (Transportation, Per Diem, Misc.)		$3,000
I. TOTAL TRAVEL (G + H)	$4,500	$8,000
J. Other Direct Costs		
1. Expendable Materials $ Supplies	$1,500	$750
2. Publication Costs/Page Charges		
3. Consultant Services	$500	$250
4. Computer Services		
5. Other (Conference registration)		$1,000
K. TOTAL OTHER DIRECT COSTS (J.1-5)	$2,000	$2,000
L. TOTAL DIRECT COSTS (C + F + I + K)	$22,000	$25,500
M. INDIRECT COSTS (20% of direct costs incurred in dinars, exluding items G. H $ I)	$3,500	
N. GRAND TOTAL (L + M)	$25,500	$25,500

P. I. Signature — 18-Jul-89 *Date*

Institutional Representative Signature — 18-Jul-89 *Date*